Boletim de Pesquisa e Desenvolvimento 08
ISSN 1677-2229
Dezembro, 2005

Postharvest Porometer to Study Transpiration and to Measure Vapor Pressure Deficit

Embrapa

ISSN 1677-2299
Dezembro, 2005

Empresa Brasileira de Pesquisa Agropecuária
Embrapa Hortaliças
Ministério da Agricultura, Pecuária e Abastecimento

Boletim de Pesquisa e Desenvolvimento 08

Postharvest Porometer to Study Transpiration and to Measure Vapor Pressure Deficit

Adonai Gimenez Calbo

Brasília-DF
2005

Exemplares desta publicação podem ser adquiridos na:

Embrapa Hortaliças
BR 060 Rodovia Brasilia-Anápolis km 9
Caixa Postal 218
70359-970 Brasília-DF
Telefone (61) 3385-9009
E-mail: *sac.hortalicas@embrapa.br*

Supervisor editorial: Sieglinde Brune
Normalização bibliográfica: Rosane Mendes Parmagnani
Editoração eletrônica: José Miguel Santos

1ª edição
1ª impressão (2005): 50 exemplares

Calbo, Adonai Gimenez
Postharvest porometer to study transpiration and to measure vapor pressure defict / Adonai Gimenez Calbo. — Brasília : Embrapa Hortaliças, 2005.
20 p. ; (Embrapa Hortaliças. Boletim de Pesquisa e Desenvolvimento, 08)

ISSN 1677-2229

1. Porômetro. 2. Transpiração. 3. Déficit de pressão de vapor. 4. Resistência difusiva. 5. Volumetria. I. Título. II. Série.

CDD 620.116 (21. ed.)

Sumário

Postharvest Porometer to Study Transpiration and to Measure Vapor Pressure Deficit

Adonai Gimenez Calbo[1]

Abstract

The postharvest porometer is an instrument developed to measure transpiration, diffusive resistance and water vapor pressure deficit using manometry at constant volume, or using volumetry at constant pressure. This porometer is made of a transpiration chamber, with an hermetic closing lid, having a sample holder and a ventilator. This transpiration chamber is connected to an external water column manometer with a movable pipette. In a constant temperature assay, the water vapor pressure increase (ΔP) and the water vapor volume (ΔV) were proportional to the volumes of water vaporized over the ventilator. Using an excess of liquid water this pressure increment is an estimate of the atmospheric water vapor pressure deficit. For laboratory air samples, manometric water vapor pressure deficits measurements correlated well (r=0,976) with the water vapor pressure deficits calculated using dry and wet bulb temperatures measured in a ventilated psychrometer. The postharvest porometer transpiration measurement accuracy is such that the chamber dead volume (V) multiplied by the declivity ΔP/ΔV, determined according to the amount of transpired water vapor yield the local barometric pressure, with an error of about 1%. Examples of the post-harvest porometer use to calculate diffusive resistance, or conductance, and of the unstirred air layer thickness are presented. The post-harvest porometer is simple, robust, does not require calibration and can be used to compare genotypes and in postharvest studies such as those involved in waxing and cure treatments.

Index terms: diffusive resistance, manometry, porometer, transpiration, vapor pressure deficit, volumetry.

[1] Eng. Agr., PhD, Embrapa Hortaliças, Brasília-DF. E-mail: *adonai@cnph.embrapa.br*

Porômetro de Pós-Colheita para Estudar Transpiração e Medir Déficit de Pressão de Vapor

Resumo

O pôrometro de pós-colheita é um instrumento para medir transpiração, resistência difusiva e déficit de pressão de vapor por manometria a volume constante e por volumetria a pressão constante. É constituído de uma câmara de transpiração com fechamento hermético contendo um suporte de amostras sobre um ventilador e externamente um manômetro de coluna de água com pipeta graduada móvel. Sob temperatura constante, o déficit de pressão de vapor (ΔP), e o volume de vapor de água (ΔV) foram proporcionais aos volumes de água vaporizados. Com o uso de um excesso de água este aumento da pressão de vapor iguala-se, em módulo, ao déficit de pressão de vapor do ar na câmara de transpiração. Para amostras do ar atmosférico no laboratório, o déficit de pressão de vapor foi calculado a partir das temperaturas de bulbo seco e úmido em um psicrômetro ventilado e por manometria. A correlação entre estes dois métodos foi de 0,976. A acurácia das medidas de transpiração é tal que o produto do volume morto da câmara (V) pela declividade ($\Delta P/\Delta V$) determinada pelo vapor de água liberado no processo iguala-se à pressão barométrica, com erro inferior a 1%. Um exemplo experimental do uso do porômetro de pós-colheita em cenoura é apresentado juntamente e os detalhes para obter a resistência difusiva e espessura da camada laminar. O porômetro de pós-colheita é um porômetro de difusão simples, robusto, que poderá ser usado em estudos de efeito de cêras, na seleção de cultivares e em variados outros estudos de fisiologia de pós-colheita.

Termos para indexação: déficit de pressão de vapor, manometria, porômetro, resistência difusiva, transpiração, volumetria.

Introduction

Water vapor manometry and volumetry had not appeared among surveyed methods to measure transpiration and diffusive resistance. The old literature survey was based on the extensive methodological review published by Slavick (1974) and the recent literature survey was done using Biological Abstracts and CAB for scientific articles, and the United States Patent Office for patent claims. Such survey result was unexpected, since manometry and volumetry has been valuable tools in biochemical assays, that include respiratory and photosynthetic gas exchange studies, even after the development of modern methods such as the gas chromatograph (NERY; CALBO, 1994).

The use of manometry and volumetry in measurements of transpiration and diffusive resistance can be made considering that the transpiration rate (T_r) is proportional to the organ diffusive resistance coefficient R_d and to the water vapor pressure deficit DPV, of the plant surface in comparison with the ambient air (NOBEL, 1991):

$R_d T_r = DPV$ Eq. 1

In a transpiration chamber with a dead volume V at temperature T the following differential equation can be written for an infinitesimal evolution of transpired water vapor molecules (dn):

$Vde = -R T dn$ Eq. 2

where **e** is the water vapor pressure and R is the ideal gas parameter. Dividing Eq. 2 by the time increment (dt), it follows that

$V\mathbf{d}e / dt = -R T T_r$ Eq. 3

where $T_r = dn/dt$ and $\mathbf{d}e = -\mathbf{d}DPV$. Additionally, replacing T_r by its DVP value from equation 1 yields:

$V\ dDPV/ dt = -R T DPV/ R_d$ Eq. 4

Making $b=RT/(V R_d)$, the integration of equation 4 between T_{r0} and T_r and between 0 and t generates:

$DPV = DPV_0\ e^{-bt}$ Eq. 5

From equation 5 it is evident that b expressed as the inverse of the time unit. If the postharvest porometer is measuring pressure change p, that increases from 0 to DPV_0, then equation 5 can be rewritten as:

$p = DPV_0\ (1 - e^{-bt})$ Eq. 6

In equation 6 p is the water vapor pressure generated by transpiration, during a time period t and DPV_0 is the initial vapor pressure deficit, between the product surface and the transpiration chamber air. DPV_0 and b are parameters (Eq. 6), obtained from a statistical curve fitting between measured water vapor pressure points produced as a function of time. The parameter b is then, used to calculate Rd with the expression:

$R_d = RT / (b\ V)$ Eq. 7

The transpired water vapor volume (ΔV) at constant pressure can be obtained from

the produced pressure increments ΔP, at constant volume, with use of the factor Φ (Eq. 8).

$$\Phi = \Delta P/\Delta V \qquad \text{Eq. 8}$$

From the ideal gas equation it can be demonstrated that the factor Φ is equal to:

$$\Phi = P_B/ V \qquad \text{Eq. 9}$$

Consequently, to test the equipment accuracy the estimate of Φ (Φ_1) obtained from ΔP and ΔV measurements in a post-harvest porometer using (Eq. 8) and was compared with a second estimate Φ (Φ_2) estimated using P_B and V (Eq. 9). In other words Φ_1 and Φ_2 should have similar values in a properly assembled porometer.

Equation 6 divided by Φ generates an expression (Eq. 11) for use of volumetry at constant pressure.

$$\Delta V = \Delta V_f (1 - e^{-bt}) \qquad \text{Eq. 10}$$

in which ΔV is the water vapor volume liberated during an assay time interval t and ΔV_f is the asymptotic water vapor volume. In equation 10 ΔV_f and b are parameters obtained by the equation to the experimental data. Evidently, using equation 1 equation 6 could also be converted to $T_r = T_{r0}\, e^{\,bt}$.

The substitution of b into equation 10 yields:

$$R_d = t\, R\, T / [V\, Ln(\Delta V/\Delta V_f)] \qquad \text{Eq. 11}$$

Using $t_{1/2}$ as the period during which the water vapor volume increases from zero to $\Delta V/\Delta V_f = 1/2$, equation 11 can be rewritten as:

$$R_d = t_{1/2}\, R\, T / [V\, Ln(1/2)] \qquad \text{Eq. 12}$$

The use of equation 12 is an approximated procedure to calculate R_d, without the use equation fitting software. The $t_{1/2}$ value referred in Eq 12 can also represent the time to reduce the water vapor pressure deficit to half ($DPV/DVP_0 = 1/2$).

The diffusive resistivity (r_1) per unity of area (A) is used for leaves and is calculated multiplying R_d by the leaf area (Eq. 13). The diffusive resistance per unit of mass (M) used as the intensive variable to be applied to voluminous post-harvest stored organs and is calculated multiplying R_d by the organ mass (Eq. 14):

$$r_1 = R_d\, A \qquad \text{Eq. 13}$$

and

$$r_2 = R_d\, M \qquad \text{Eq. 14}$$

For transpiration the resistance or its inverse the water vapor conductance coefficients expressed per unit of area are widely used by ecophysiologists, but it is overlooked by most postharvest physiologists. That seems puzzling because water loss is one of the major causes of postharvest deterioration. This low usage, possibly, is caused by the difficulty to compute the correct surface area of voluminous organs such as tuberous roots, tubers, and fruits. In this work, in particular these surfaces were approximated assuming these voluminous organs had cylindrical, conical, spherical or ellipsoidal shapes. Consequently, resistance and conductance to water vapor were previously reported per unit of product mass as used by Burton (1982).

For sake methodological simplicity the vapor pressure deficit (DPV) was considered the driving force for transpiration, since the developed method make use of pressure and volume measurements. However, in the literature it is more frequent to consider the use of water vapor concentration gradient (ΔC) as the driving force for transpiration, possibly because it is easier to estimate variables such as the unstirred laminar layer thickness. More recently the water vapor molar fraction gradient is being used as the driving force for transpiration, which yield resistance factors that are not influenced by the local barometric pressure and is less influenced by temperature (Nobel, 1991). Fortunately, these resistance and conductance coefficients can be easily converted knowing the local barometric pressure and the temperature.

The objective of this work is then to describe the postharvest porometer its working procedures, its limitations and potentialities. Emphasis is also given to prove its correct functioning and methods to measure transpiration, water vapor pressure deficit and diffusive resistance, or its inverse the conductance.

Material and Methods

Construction

The postharvest porometer was made using as the transpiration chamber (Fig. 1) a Clock® pressure cooker with 4,395 L or 7.241 L or a Lares® pressure cooker with 4,506 *L*. Plant samples were placed on a metallic net centered over ventilator, which served as the sample holder. A 12 V computer ventilator was operated at 3 V dissipating 0,15 watts. Pressure and volume were measured in a water column manometer (Fig. 1) made of a 100 ml graduated pipette immerged in a water reservoir. The pipette immerged portion was controlled manually adjusting the pipette height, by friction, in a grasp.

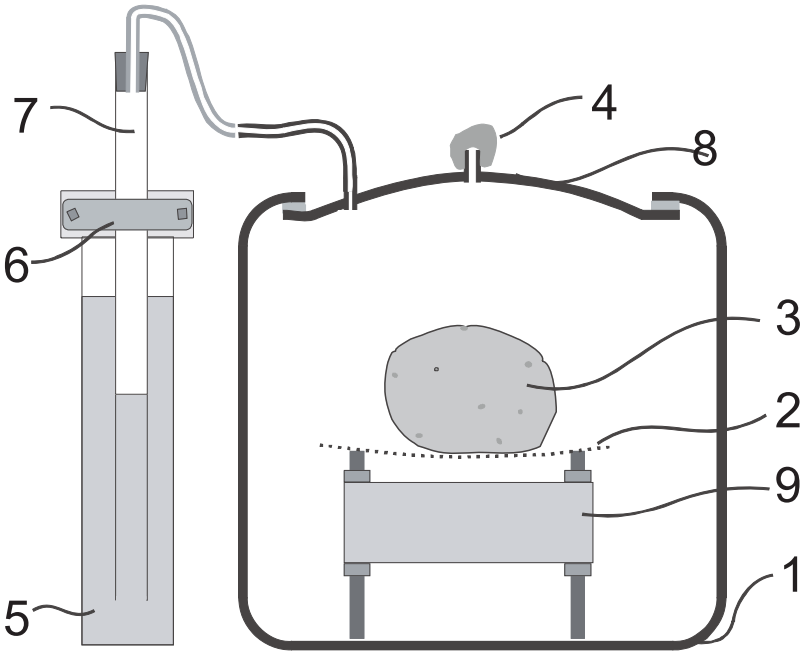

Fig. 1. Post-harvest porometer with a transpiration chamber, an electric fan and a manometer with a pipette which height is adjustable in a grasp. 1- Transpiration chamber, 2- metallic screen, 3- plant organ, 4 plastic sealant, 5- manometer water reservoir, 6 – grasp, 7- pipette, 9- transpiration chamber lid with air escape and 9 ventilator.

Volumetry

The pipette height was zeroed the sample was placed into the transpiration chamber, which was rapidly closed, letting the air escape opened. The transpiration measurement was started by closing the air escape with a plastic sealant. Constant pressure was maintained by suspending the pipette while water in its manometer pipette was always returned to the reservoir water surface level. The transpired water volume in milliliters (ΔV), measured in the pipette was registered in regular time intervals, for the subsequent Rd estimation with equation 7 or equation 12.

Manometry

The pipette 100 *mL* mark was leveled with the manometer water surface level (ΔP=0mm). After placing the organ in the sample holder, the transpiration chamber was rapidly closed, with its air escape opened. The transpiration measurement was started by blocking the air escape with a plastic sealant. Transpiration increases the pressure and the pipette was repeatedly lowered, to maintain the internal meniscus at the 100 *mL* mark. This pipette height adjustment was used to maintain the system dead volume constant. ΔP was the water height difference read in the manometer, during an assay time period (t). Measurements of ΔP in regular time intervals were used to estimate Rd with equation 7 or with equation 12.

Coefficients relating transpiration and its driving gradients

The resistance to water vapor transport per unit area, the resistivity (Eq. 11), in the transpiration process was developed considering that the water vapor pressure gradient (DPV) is the driving force for the occurrence of transpiration, and the measured resistivity (r) was given in mol m^{2} s mm^{1}.

In a second form to address transpiration the water vapor concentration gradient (ΔC) in mol m^{3}) is the considered driving force. To this the water vapor pressure deficit (DPV) is converted to a concentration gradient ΔC, according to the Clapeyron equation, dividing DPV by the product RT (ΔC = DPV/RT). And as consequence this resistance (r_1) with units o s m^{1} is given by:

$r_1 = r / RT$ Eq. 15

Nowadays after Farquhar et al (1978) and Nobel (1991) the best approach seems to considering the water vapor molar fraction (ΔN) gradient, which is a dimension less driving gradient for transpiration. The advantage of using molar fraction is that the calculated resistivity (r_2) is independent of the local barometric pressure (P_B). This transformation is made dividing r (Eq. 11) by the barometric pressure (Pb)

$r_2 = r / P_B$ Eq. 16

consequently, in this case the resistivity is given as m^{2} s mol^{1}.
Correspondent water vapor conductances per unit of area (g, g_1 and g_2) are calculated as the inverse value of the correspondent resistivities (r, r_1 and r_2).
Consequently, g is in mol^{1} m^{2} mm s^{1}, g_1 is m s^{1}, and g_2 is in mol m^{2} s^{1}.
In the metric system, considering the manometric water vapor was measured in milimeters of water column, the ideal gas constant value R used was R=0.8445

m^3 mm mol^{-1} K^{-1}. Using this R value all r and g values can be calculated exactly as explained.

Unstirred air layer over the product

The thickness of the unstirred layer depends on wind velocity and on the organ size and shape (NOBEL, 1991). To estimate this layer thickness product is wetted with an sponge with water, for some products a wetting agent needs to be added to water for wetting. Measurement is done as described before. The laminar layer thickness (δ) can be calculated with the expression

$$\delta = r\ D \qquad \text{Eq. 20}$$

where D is the water vapor diffusion coefficient in air at the assay temperature and pressure (Nobel, 1991).

Porometer test

To verify whether the porometer is functioning properly, equation 8 is fitted to pairs of ΔP and ΔV points, obtained alternating manometric readings with volumetric readings after different transpiration assay periods. This can be done reversibly in any single postharvest porometer measurement. Alternatively, pressure measurements ΔP were performed after the injection of known amounts of dry air. The declivity Φ was calculated with equation 9. A second estimate of Φ (Φ_2) was obtained dividing the local barometric pressure P_B by the transpiration chamber dead volume V (Eq. 9). If these two estimates of Φ were similar the porometer is functioning correctly and without leakage.

Water vapor release test

A second test to evaluate if the the post-harvest porometer yield correct responses was made releasing known amounts of water vapor in the transpiration chamber. For this purpose a small pipette tip was coupled to a plastic capillary by a needle, and filled with water. The small pipette was closed with a plastic sealant and placed 0,7 m above the transpiration chamber base. The capillary inserted through the chamber air escape was fixed to the ventilator body, allowing a slight capillary tip frictioning over the ventilator fan.

After closing the transpiration chamber, and closing the air escape with a plastic sealant, the water sample was applied by opening the small pipette tip long enough to deliver the desired water volume. Broken into small droplets by the ventilator fan is carried by the wind and evaporated in the vaporized sample was measured using the previously described manometric and volumetric procedures.

To measure water vapor pressure deficit, a larger water sample, typically 0,5 *mL*, was vaporized in the transpiration chamber. The water vapor pressure deficit was then equaled to the water vapor pressure increment. Correction for the injected water volume was done directly in the pipette positioning.

Psychrometry

The relative humidity (Eq. 17) was calculated according to the saturating water vapor pressure (e_S) at the temperature (T) using equation 18 from dry and wet bulb

thermometers in an aspirated psychrometer (ASAE, 1998).

$UR\% = 100(e_S\text{-}DPV)/e_S$ Eq. 17

$Ln(e_S/R) = (A+BT+CT^2+DT^3+ET^4)/(FT-GT^2)$ Eq. 18

In equation 16, valid between 273.16 and 533.16 degrees Kelvin, T is the temperature in Kelvin and the parameters for calculation are: R=22105649,25; A = -27405.526; B=97.5413; C= -0.146244, D=0.1255 10^{-3}; E= -48502 10^{-7}; F=4.34903; G=0.39381 10^{-2}. The wet bulb line equation given by equation 19 was also used.

$(e_U - e_S) = (T - T_U)\ P_B\ 0.0016286\ /(2.501 - 0.002361\ T)$ Eq. 19

In equation 19 e_U is the saturating vapor pressure at the wet bulb temperature (T_U), e_S is the water vapor pressure at the dry bulb temperature (T) and P_B is the barometric pressure. With equations 18 and 19 a GWBASIC computer program was written to generate values of UR%, and water vapor pressure as a function of the dry and wet bulb temperatures, for a given local barometric pressure. In table 1 the saturating water vapor pressure as a function of temperature is presented in millimeters of water column at the standard atmospheric pressure. This and other relevant data derived from equations 17, 18 and 19 can also be obtained in other temperatures and barometric pressures.

Results and Discussion

Resistance, conductance and $t_{1/2}$ values

In Fig. 5A an observer may estimate of maximum value ΔV_f as 80mL, $\Delta V_f/2$ is, consequently, 40 mL and the time to reach this $\Delta V_f/2$ observed accordingly was 95 s. With this time interval ($t_{1/2}$) the diffusive resistance R_d calculated using the gas constant (R=0,8445 mm H_2O s mol^{1}) with equation 12 is then 4824385 mm H_2O s mol^{1}. A more exact Rd estimate can be made with equation fitting. This simplified $t_{1/2}$ procedure to calculate Rd can be used in the postharvest porometer working either in the constant volume manometry mode and in the constant pressure volumetric mode.

Manometry example

Figure 5B illustrates a typical vapor pressure augmentation during a ´Brasília‘ carrot root transpiration measurement. The least square fit of equation 6 to this data set yield $p = 88.37(1- e^{-0.008054\ t})$. The diffusive resistance (Rd = 4432415 mm H_2O s mol^{1}) was calculated according to the parameter b (0.008054 s^{1}) with use of equation 7, temperature 298.44 °K, with the gas parameter R equal to 0.8445 m^3 mm K^{-1} mol^{-1} and a transpiration chamber dead volume of 7.16 *L* minus are the other values used in this calculation.

The initial transpiration (1.99 10^{5} mol s^{1}) at the postharvest porometer closure was obtained dividing the parameter DPV_0 (88.37 mm H_2O) by Rd (Eq. 1). Using the Clapeyron equation this transpiration rate could be converted to m^3 s^{1} just multiplying this value by a factor ($RT\ P_B^{1}$). Dividing this value by the carrot surface area yield

water vapor resistance coefficient 1.21 10^{-3} mol s^{-1} m^{-2} or 32.9 ml s^{-1} m^{-2}. Is equivalent to consider the water vapor concentration (mol m^{-3}) gradient as the driving force for transpiration to express this diffusive resistance in s m^{1}, in this example 290 s m^{-1}. The resistivity coefficient 2,9 m^2 s mol^{1} using water vapor molar fraction gradient is obtained dividing r by P_B (Eq. 16). According to Nobel this diffusive resistance, or it inverse the conductance, is independent of the local barometric pressure and is also less affected by the temperature. For this reason some recent transpiration and photosynthetic studies have diffusion resistance in m^2 s mol^{1} instead of the ancient presentation in s m^{1} is preferred. This resistivity is similar to a crop leaf with opened stomata (NOBEL, 1991).

The transpiration in g H_2O kg^{-1} day^{-1} is obtained multiplying the transpiration (mol s^{1}) by the water molecular mass (18g), and adjusting the time scale. This weight loss, however, is more meaningful if divided by the transpiration driven force, the DPV0 in Pa. The conductivity result expressed in g H_2O kg^{-1} day^{-1} Pa^{-1} considering 1mm H_2O equal to10.13Pa is 62.4 g H_2O kg ^{1} day ^{1} Pa ^{1}. That is a form of water vapor conductance per unity of fresh matter similar to that used in the Burton (1982) postharvest studies, for potato and other crops.

Transpiration, a volumetry worked example

Transpired water vapor volume data obtained at constant pressure (Fig 5B) was fitted to equation 13, yielding $\Delta V = 73.42\ (1 - e^{-0.00816\ t})$, where ΔV_f = 73.42 ml and b = 0.00816 s^{1}. Other calculations are identical to those previously described for constant volume manometry.

The initial water vapor pressure deficit (DPV_0) can be obtained multiplying the fitted ΔV_f (93.42 *mL*) by the transpiration chamber factor Φ (Eq.8). The value of Φ 1302 mm H_2O l^{1} was calculated substituting the local barometric and the transpiration chamber volume into Eq. 9. The product of Φ by ΔV_f yield an initial vapor pressure deficit of 000 mm of water column. With this initial water vapor pressure deficit (DPV_0) the initial transpiration (T_r) calculated with equation 1 was 122 mm H_2O.

Unstirred air layer over the product

The resistance to the water vapor transport involves at least, the water vapor diffusion through an unstirred air layer facing organ surface. Additionally, there are other resistances through dermal structures such as the cuticle and the lenticels. The thickness of the unstirred layer is reduced by the wind velocity and depends on the organ size and shape (NOBEL, 1991).

To estimate the unstirred layer thickness the organ surface can be wetted with an sponge. If necessary an auxiliary wetting agent is added to water. The laminar layer thickness (δ) can is then calculated with the expression:

$\delta = r_1 D$ Eq. 20

where D is the water vapor diffusion coefficient in air at the assay temperature and pressure. Measurement of r_1 in this wetted 'Achat´ potato tuber was done as described before and yield a resistivity r_1 of 110 s.m^{-1}.

Replacing r_1 (110 $s.m^{-1}$) and D in air at one atmosphere and 20 °C (2.4 10^{-5} m^2 s^{-1}) in equation 20 yield an average unstirred air layer thickness (δ) of in 2.6 mm. The procedure herein suggested is a modification of the wet paper leaf replica procedure recommended by Nobel (1991) to estimate the laminar layer thickness without using a sophisticate physical approach to obtain na estimate in this problem.
The ventilator fan can be turned of for measurements of transpiration and diffusive resistance of organs under low ventilation, which is a relevant and prevalent condition in most post-harvest physiology storage environments (LUENGO; CALBO, 2001).

Physical validation

The confirmatory assays presented in the last part of this work are not necessary in the ordinary use of the postharvest porometer, however, it is a form to prove that the postharvest porometer is a reliable instrument that is working properly.
In a first validation assay the declivity coefficient between the injected air volume and the pressure generated at constant volume (Fig. 2) is the conversion factor (Φ_1) (Eq. 8). For the 4.506 L pressure chamber Φ_1 was 2058.5 mm L^{-1} (Eq. 8) while the value Φ_2 = 2070 mm L^{-1}, calculated with equation 9, was very similar to Φ_1. This similarity is an indication that the postharvest porometer is correct and consequently the Φ_1 multiplied by the chamber volume yield a local barometric pressure estimate of 9275 mm of water column, which is similar to the 9275 mm of water column local barometric pressure (682 mm Hg).

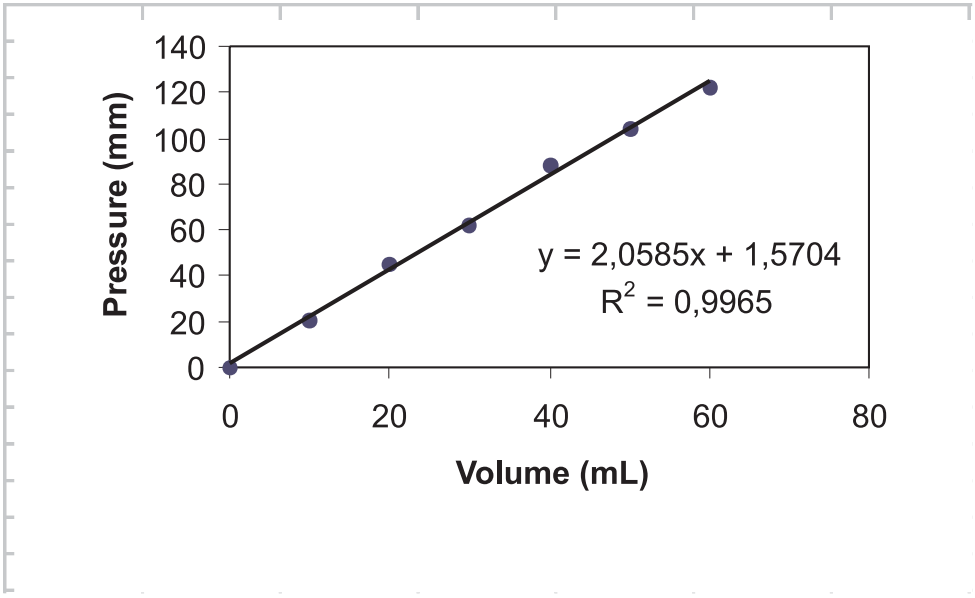

Fig. 2. Pressure developed at constant volume as a function of the injected air volumes in a hermetic 4.506 L transpiration chamber.

In a second post-harvest porometer validation assay, the water vapor pressure (ΔP) generated at constant volume was proportional to the mass of water injected and vaporized inside the transpiration chamber (Fig. 3A). Similarly, the volumes of water vapor formed at constant pressure, were proportional to the volumes of water vaporized in this small pipette method (Fig. 3B). These water vaporization results are consistent with isothermal water vapor pressure and the isothermal water vapor volume calculated with the Clapeyron equation (MOORE, 1972). This result make it evident that the postharvest porometer does not need to be calibrated. Other types of

ventilated diffusion porometers based on relative humidity sensors requires calibration in environments with adjusted relative humidity, in closed systems (WINDYON; HATES, 1960) which is a time consuming approximated process. Alternatively, in certain non ventilated diffusion porometers calibration is performed using Ficks first law with standard perforated plates and other devices (SLAVICK, 1974).

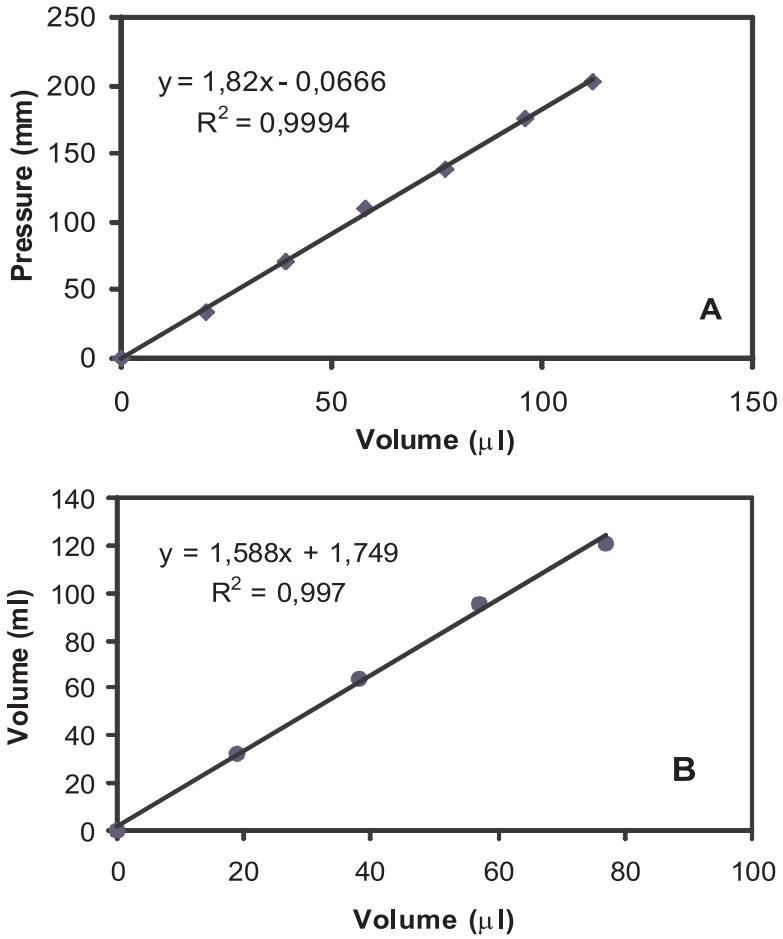

Fig. 3. Developed pressure and developed volumes caused by the vaporization of known amounts of liquid water inside a 7.24 L transpiration chamber. A – Manometry at constant volume under 24.3 °C. B – Volumetry at constant pressure 25.5 °C.

Another evidence for the correct post-harvest porometer functioning in the manometric mode, comes from water vapor pressure deficit measurements which were obtained using dry/wet bulb psichrometer and with this manometric method in the same air sample, at the same temperature. Air vapor pressure deficit measured with both methods were similar (Figure 4).

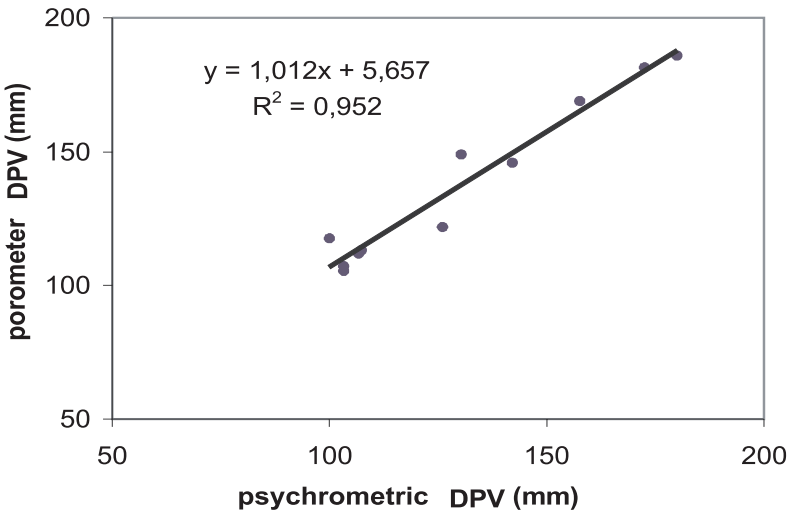

Fig. 4. Water vapor pressure deficit measured by manometry at constant volume in function of the water vapor pressure deficit calculated with dry and wet bulb temperatures from a ventilated psycrometer.

Possible isothermal deviations

Leaf and chamber temperature are used to calculate transpiration and diffusive resistance in porometers with relative humidity sensors such as those patented by Eckles (1982) and CRUMP; CRUMP (1979). In the post-harvest porometer these temperatures are not directly used to calculate transpiration and diffusive resistance (Eq. 12 e 15). This characteristic, however, does not reduces the significance of temperature, since it causes changes in the saturating water vapor pressure and in the partial pressure of gases measured at constant volume. Related changes also occur in isobaric assays in which water vapor volume measurements are made. When the transpiration chamber temperature and the product temperature can not be considered equal, and constant, during an assay, then the water vapor quantitative analysis become difficult, even in sophisticated porometers (ECKLES, 1982), which operates in steady state regime, with real time thermal correction.

As in other porometers, transpiration should occur without water condensation in the porometer walls. Besides this additional temperature guideline the following temperature related aspects should be considered:

1- It is not recommended but, equations 6 and 10 can be employed when the organ temperature is greater than the transpiration chamber temperature, however **e** values close and higher than the water vapor saturation, at chamber temperature, needs to be eliminated, among other reasons because water condensation will occur in the chamber walls. The useful fraction of the measuring range is given by the ratio q, defined by the following expression:

$$q = (e_{so} - e_{ar0}) / (e_{sc} - e_{ar0}) \qquad \text{Eq. 21}$$

In equation 21 $\mathbf{e}_{so}$ is the saturating water vapor pressure at the organ surface temperature, $\mathbf{e}_{ar0}$ is the initial air water vapor pressure in the transpiration chamber and $\mathbf{e}_{sc}$ is the saturating vapor pressure at the transpiration chamber wall temperature. Even with the elimination of the data close and above $\mathbf{e}_{sc}$, there is a loss of transpiration estimate quality when condensation starts in the chamber wall, the gas exchange pattern is changed while the air vapor pressure stays greater than $\mathbf{e}_{sc}$. To avoid this transpiration measurement error, q should be larger than 0,7 and data can only be gathered while $\mathbf{e} < \mathbf{e}_{sc}$.

2- Additionally, for the same reason, when the organ temperature is higher than the transpiration chamber temperature the procedure to calculate R_d from $t_{1/2}$ visual procedure becomes infeasible.

Besides these temperature guidelines it is important to consider how much physical and biological heat sinks and sources do effect any porometer functioning. For the post-harvest porometer, in particular, the following heat sources and sinks are relevant:

1- To reduce the unstirred laminar air layer thickness over the organ surface the ventilator was used. The heat dissipated by the ventilator, however, should not cause transpiration chamber temperature increment larger than 0,1°C.

2- How much heat was removed by the transpiration induced cooling was calculated considering air starting with an initial relative humidity of 75%, at 30 °C. The calculated amount of vaporized water to saturate a 7.24 liters transpiration chamber in this condition is 0,055g. The heat to vaporize this amount of water is 34,1 cal. The calorific capacity of the 1550 g aluminum transpiration chamber is 335 cal °C ^{1}. Consequently, about 0.1°C cooling is calculated for this heat absorption. Similar cooling estimates at initial temperatures of 20 °C and 10 °C were 0.05 °C and 0.025 °C, respectively. For most uses those temperature reductions induced by latent heat exchange can be disregarded.

3- Respiration causes heating, converting the vital heat of organs such as tomatoes (PANTASTICO, 1975) it can be estimated that at 10 °C one kg of tomatoes produces around 0.01 watts, which is a negligible heat source for this porometer.

Organ respiration could also cause a non thermal error in a post-harvest porometer reading, such theoretical error is a pressure reduction proportional to the respiration rate. This respiratory pressure reduction is caused by the large CO_2 water solubility which is about 30 times larger than the O_2 solubility. Fortunately, this respiratory induced pressure reduction is inversely related to the chamber dead volume, plus organ intercellular air volume. With the equations derived by Nery & Calbo (1994) it can be demonstrated that this respiratory pressure reduction is negligible when the hermetic chamber dead volume is much larger than the organ volume.

Pipette evaporation error

At constant volume, the pressure increment caused by water vapor transport from the pipette to the transpiration chamber was not detectable, this transport should have been dumped through the connecting tube which had an internal diameter of 2 mm and a length of 1.5 m. In addition, the transient deviations of the isovolumetric condition, caused by wrong pipette positioning was always smaller than 0,1 thousandth of the transpiration chamber volume. In volumetry, at constant pressure, the evaporation error, however, can be larger, but is always smaller than the water vapor mole fraction in the air multiplied by the pipette air volume. An idea about the magnitude of this error was obtained considering that at 20°C, under a pressure of one atmosphere, the water vapor molar fraction in air is 2.39%. Thus, if a relative humidity of 80% is considered at the beginning, then, the error caused by the volume of water evaporated is at most 0,48%, of the pipette volume. It is evident, however, that this error can be eliminated using an oil manometer, which, however, seemed to be less convenient.

New potentialities

With a light entrance and an appropriate ventilation leaves can be also studied in the post harvest porometer, initially in laboratory assays. With modifications the postharvest porometer can be used as a steady-state porometer. For use as a null set steady-state mode a container with a desiccating agent and an air circulation system with a precise air flow adjustment needs to be added to remove water vapor as it is

formed in the transpiration, similarly to the process used in the Winston & Hates (1960) porometer. In the post-harvest porometer, steady-state operation can be performed fixing the initial pressure and adjusting the air flow (F) between the transpiration chamber and the desiccation container. Transpiration could be then estimated from the measured air flow using the expression:

$T_r = F \Delta P/RT$ Eq. 22

Volumetry versus manometry

Constant pressure volumetry is an unique gasometric procedure to follow transpiration directly, without convertions (Fig. 5). Other direct methods to assess transpiration involves liquid water mass or volume estimates and are consequently non gasometric methods. Two common procedures of this sort are potometry and detached leaf weighing (SLAVICK, 1974). Potometry, however, can only be considered a direct method to measure transpiration, whether the plant volume do not change during the assay. Weighing detached organ is a direct method that, however, it has severe described limitations, when applied to leaves (SLAVICK, 1974).

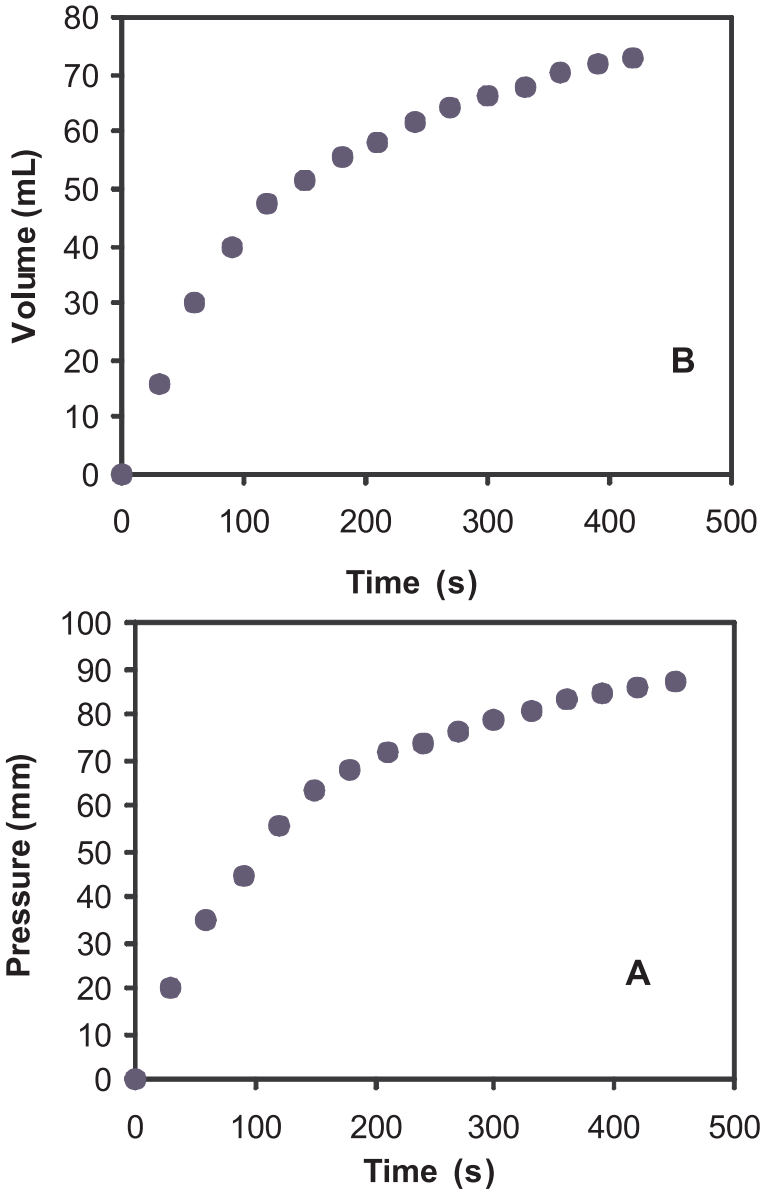

Fig. 5. Typical transpired water vapor volume curve measured at constant pressure A, and typical transpired water vapor pressure developed at constant volume B during transpiration measurements of a 79 g 'Brasília' carrot root, inside a 7,24 L transpiration chamber, at 25,9 °C, using the ventilator.

The qualities of the volumetry at constant pressure are valuable to teach transpiration because it is ease and it is a surprise to most students the observation of the large water vapor volumes released in the transpiration process. However, under some aspects manometry at constant volume had the following superior qualities: 1) The water evaporation in the pipette theoretically null. 2) In the manometric procedure the manometer can be miniaturized or even be replaced by an electronic sensor.

Conclusions

1. Transpiration, water vapor pressure deficit, resistance and conductivities are reliably measured with the postharvest porometer.
2. Evidence for proper post-harvest porometer functioning is obtained injecting a known amount of air and calculating the local barometric pressure, if the estimate is correct the equipment is without leakage.

Table 1. Saturation water vapor pressure in millimeters of water column as a function of temperature.

	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	62.56	63.02	63.48	63.94	64.40	64.87	65.34	65.81	66.29	66.77
1	67.25	67.74	68.22	68.72	69.21	69.71	70.21	70.71	71.22	71.73
2	72.25	72.76	73.28	73.81	74.34	74.87	75.40	75.94	76.48	77.02
3	77.57	78.12	78.67	79.23	79.79	80.36	80.93	81.50	82.07	82.65
4	83.24	83.82	84.41	85.01	85.60	86.20	86.81	87.42	88.03	88.64
5	89.27	89.89	90.52	91.15	91.78	92.42	93.07	93.71	94.36	95.02
6	95.68	96.34	97.01	97.68	98.35	99.03	99.72	100.41	101.10	101.79
7	102.49	103.20	103.91	104.62	105.34	106.06	106.79	107.52	108.25	108.99
8	109.74	110.48	111.24	111.99	112.76	113.52	114.29	115.07	115.85	116.64
9	117.43	118.22	119.02	119.82	120.63	121.45	122.26	123.09	123.91	124.75
10	125.59	126.43	127.28	128.13	128.99	129.85	130.72	131.59	132.47	133.35
11	134.24	135.14	136.04	136.94	137.85	138.76	139.69	140.61	141.54	142.49
12	143.42	144.37	145.32	146.28	147.24	148.21	149.19	150.17	151.16	152.15
13	153.15	154.15	155.16	156.18	157.20	158.22	159.26	160.30	161.34	162.39
14	163.45	164.51	165.58	166.65	167.74	168.83	169.92	171.02	172.12	173.24
15	174.35	175.49	176.61	177.75	178.79	180.04	181.20	182.36	183.53	184.71
16	185.89	187.08	188.28	189.48	190.69	191.91	193.13	194.37	195.60	196.85
17	198.10	199.36	200.62	201.89	203.17	204.46	205.75	207.06	208.36	209.68
18	211.00	212.33	213.67	215.01	216.36	217.72	219.09	220.47	221.84	223.24
19	224.63	226.04	227.45	228.87	230.30	231.74	233.18	234.63	236.09	237.56
20	239.03	240.52	242.01	243.51	245.01	246.53	248.06	249.59	251.12	252.68
21	254.23	255.80	257.37	258.96	260.55	262.15	263.76	265.37	267.00	268.63
22	270.27	271.93	273.59	275.26	276.93	278.62	280.32	282.02	283.74	285.46
23	287.19	288.93	290.69	292.44	294.21	295.99	297.78	299.58	301.39	303.20
24	305.03	306.86	308.71	310.56	312.43	314.30	316.19	318.08	320.00	321.90
25	323.83	325.76	327.70	329.66	331.62	333.60	335.58	337.58	339.58	341.60
26	343.62	345.66	347.71	349.77	351.83	353.91	356.00	358.10	360.22	362.64
27	364.47	366.62	368.77	370.94	373.11	375.30	377.50	379.71	381.93	384.17
28	386.41	388.67	390.94	393.21	395.50	397.81	400.12	402.45	404.78	407.13
29	409.49	411.87	414.25	416.65	419.06	421.48	423.91	426.36	428.81	431.28
30	433.78	436.26	438.77	441.21	443.82	446.37	448.92	451.49	454.08	456.67
31	459.28	461.90	464.54	463.70	469.85	472.52	475.21	477.91	480.62	483.35
32	486.09	488.84	491.61	494.39	497.19	500.00	502.82	505.66	508.50	511.37
33	514.25	517.14	520.05	522.97	525.90	528.85	531.81	534.79	537.78	540.79
34	543.81	546.85	549.90	552.96	556.04	559.14	562.25	565.37	568.51	571.67
35	574.84	578.02	581.22	584.44	587.67	590.92	594.18	597.46	600.75	604.06
36	607.39	610.73	614.09	617.46	620.85	624.25	627.67	631.11	634.57	638.04
37	641.52	645.02	648.55	652.08	655.63	659.20	662.79	666.39	670.01	673.65
38	677.31	680.98	684.67	688.37	692.09	695.83	699.59	703.37	707.16	710.97
39	714.80	718.65	722.51	726.39	730.29	734.21	738.15	742.10	746.08	750.07
40	754.08	758.11	762.15	766.22	770.30	774.41	778.53	782.67	786.83	791.01

References

ALVIN, P. T. A new type of porometer for measuring stomatal opening and its use in the field. **UNESCO and Zone Research**, v. 25, p. 325-329, 1965.

ASAE Psychrometric equations. Disponível em: < http://aeserver.ageng.ndsu.nodak.edu/envr/PsycEqns.htm>. Acesso em: 29 nov. 1998.

BURTON, W. G. **Postharvest physiology of food crops.** New York: Longman, 1982.

CALBO, A. G. **Porômetro de pós-colheita para observar transpiração e calcular resistência difusiva**. PI BR 0104475-3, 2001.

CALBO, A. G.; SILVA, W. L. C.; TORRES, A. C. Ajuste de funções não lineares de crescimento. **Revista Brasileira de Fisiologia Vegetal,** Londrina, v. 1, n. 1, p. 9-18, 1989.

CRUMP, T. J.; CRUMP, J. M. **Apparatus for measuring the diffusive resistance of plant stomata**. United States Patent. US4160374, 1979.

ECKLES, R. D. **Porometer and method for stomatal measurements**. United States Patent. US4312218, 1982.

LUENGO, R. F. de A. CALBO, A. G. **Armazenamento de hortaliças**. Brasília, DF: Embrapa Hortaliças, 2001. 242 p.

MOORE, W. J. **Physical chemistry**. New Jersey: Prentice-Hall, 1972. 977 p.

NERY, A. A.; CALBO, A. G. Adapting constant-volume manometry for studying gas exchange by bulky plant organs. **Journal of the American Society for Horticultural Sciences**. Alexandria, v. 119, n. 6, p.122-129, 1994.

NOBEL, P. S. Boundary layers on air adjacent to cylinders: estimation of effective thickness and measurement on plant material. **Plant Physiology**, Mineapolis, v. 54, p. 177-181, 1974.

NOBEL, P. S. **Physicochemical and environmental plant physiology**. New York: Academic Press. 1991. 635 p.

PANTASTICO, B. **Postharvest physiology, handling and utilization of tropical and subtropical fruits and vegetables**. Westport: AVI Publishing, 1975. 560 p.

SLAVÍK, B. **Methods of studying plant water relations**. New York: Springer-Verlag. 1974. 449 p.

WINDYON, P. W.; HATES, D. H. Saturated solutions for the control of humidity in **biological research**. Ecology, v. 41, n.1, p. 232-237, 1960.

Empresa Brasileira de Pesquisa Agropecuária
Centro Nacional de Pesquisa de Hortaliças
Ministério da Agricultura, Pecuária e Abastecimento
BR 060 Km 09 Brasília/Anápolis
Caixa Postal 218 CEP 70359-970 Brasília, DF
Fone: (61) 3385-9110 Fax: (61) 3385-9042
sac.hortalicas@embrapa.br
www.cnph.embrapa.br

Embrapa Hortaliças
Ministério da Agricultura, Pecuária e Abastecimento
BRASIL UM PAÍS DE TODOS GOVERNO FEDERAL